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SOME STUDIES ON THE CHANGE OF ELECTRICAL RESISTANCE OF SELENIUM CELLS.

By F. C. BROWN and JOEL STEBBINS.

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SOME STUDIES ON THE CHANGE OF ELECTRICAL RESISTANCE OF SELENIUM CELLS.

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THIS paper deals with the effect of various agencies on the resistance of selenium cells. It has been found convenient to divide it into the following sections.

I. The Effect of Pressure on the Resistance.
II. The Light Sensitiveness at Different Pressures.
III. The Effect of Temperature on the Resistance.
IV. The Light Sensitiveness at Different Temperatures.
V. The Effect of Hydrogen Peroxide on the Resistance.
VI. The Effects of Radium.
VII. Discussion of Results.
VIII. Summary.

The selenium cells used in these experiments were of three kinds, those made by Ruhmer, by Giltay, and by ourselves. When exposed to light the Ruhmer cells increased in conductivity as much as twenty times, those made by Giltay as much as seventy times, and some of our own make about nine times. However we remade one of the Giltay cells and it then had a sensitiveness of 55 to 1. We do not known how the Ruhmer or the Giltay cells were made. In general we used the method of making outlined by Bidwell[1] although we sometimes crystallized the selenium at a higher temperature than that given by him.

[1] Phil. Mag., ser. V., Vol. 3, p. 351.

THE EFFECT OF PRESSURE ON THE RESISTANCE.

The effect of pressure alone on the selenium cells was studied in three ways, first by liquid pressures from a Cailletet pump, second by using air pressures obtained by a Norwalk four-stage compressor, third by using liquid pressures which were maintained by air pressure. A preliminary report on the experiments made by the first method was given to the American Physical Society, February, 1904.[1]

In the first method kerosene was placed in the piezometer. Pressure was obtained by pumping water into the piezometer with the Cailletet pump. The water went to the bottom of the piezometer and did not affect the insulation resistance of the selenium cell.

In order to get an idea of the temperature change due to compression of the kerosene a coil of no. 40 silk-covered copper wire was placed in the piezometer which was kept fairly constant in tap water at 13.4° C. The coil had a resistance of 39.51 ohms at 13.4° C. After the resistance of the coil had become constant it was assumed that the temperature of the kerosene was the same as that of the tap water. Then the pressure was raised to 425

$\frac{\text{kgm}}{\text{cm}^2}$	Ohms Resistance.	Time.	Temperature.
1	39.51	8 : 20	13.4° C.
425	40.11	8 : 25	
420	39.95	8 : 27	
420	39.84	8 : 29	
420	39.74	8 : 30	
420	39.64	8 : 32	
420	39.61	8 : 34	
420	39.55	8 : 39	
420	39.54	8 : 40	
420	39.53	8 : 43	
420	39.52	8 : 48	
420	39.51	8 : 54	
420	39.51	8 : 54½	
1	38.91	8 : 55	
1	39.06	8 : 57	
1	39.21	8 : 58	
1	39.31	9 : 00	
1	39.40	9 : 03	
1	39.46	9 : 06	
1	39.48	9 : 08	

[1] PHYS. REV., March, 1904.

kgm./cm². and maintained at 420 kgm./cm². until the coil had returned to the resistance that it had previously at atmospheric pressure. Then the pressure was suddenly lowered to atmospheric pressure and the kerosene was thereby cooled the same amount it had been heated previously by the compression. The resistance was measured at the intervals shown in the table above.

These observations show conclusively as is readily seen from Fig. 1, that the change of resistance in the copper coil is mainly

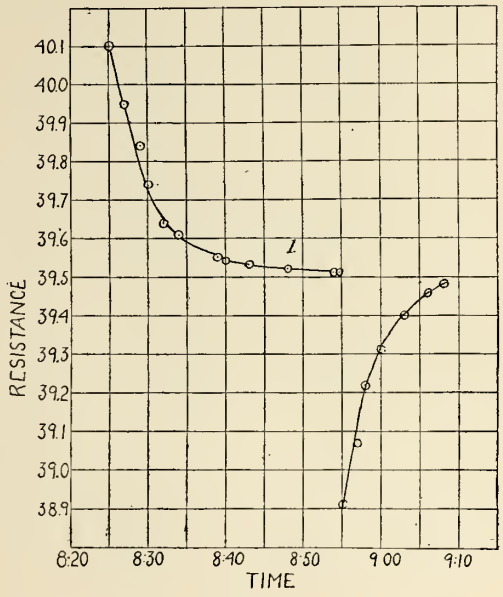

Fig. 1.

if not entirely due to temperature change. For when the kerosene is compressed and heated it returns to the temperature of the tap water and at about the same rate as that when the kerosene is cooled by letting the pressure off. We see that in thirty minutes the kerosene has returned to the temperature of the tap water when the pressure was suddenly raised or lowered 420 kgm./cm². It is to be noted that the resistance changed the same amount and oppositely when the pressure was lowered as when it was raised. Roughly one ohm change of resistance signifies seven degrees change of temperature. After 20 minutes the coil had returned

within .2 degree and in 10 minutes it had returned to within one degree. This was when the change of pressure was 420 kgm./cm^2. and when the coil was in a hard rubber case. If the pressure change were less the temperature change would be correspondingly less.

In all cases some modification of the Wheatstone's bridge method was employed to measure the resistance.

The following are some of the first observations with selenium cells under pressure. One of our own cells no. 4*a* was used. The piezometer was kept in tap water at 14.8 to 16.° C.

E.M.F. in Circuit Volts.	Pressure, kgm/cm^2.	Resistance, Ohms.
1.4	450	650,000
	270	1,300,000
	350	1,100,000
	320	1,200,000 after 10 minutes
	220	1,440,000 " 40 "
	185	1,530,000
	180	1,700,000
	160	1,720,000
	80	1,730,000
	20	1,920,000
	22	1,940,000
	1	1,990,000 after 10 minutes
10.0	1	1,170,000
	240	900,000
	400	770,000
	495	720,000
	450	770,000
	70	1,120,000
	72	1,100,000
	1	1,230,000
	1	1,200,000 after 10 minutes

These data are shown in curves 2 and 3 (Fig. 2). When 1.4 volts are used in the circuit, the average change of resistance per atmosphere is 2,200 ohms. When 10 volts are used the change of resistance is about 1,100 ohms per atmosphere. In the first case the percentage change is .11. In the second case it is .05.

Again readings were taken for cell 5 under pressure. The piezometer was packed in ice and the temperature of the room was 10° C. The electromotive force in the circuit was 1.4 volts. These

data are shown graphically in Fig. 3. The mean percentage change per atmosphere is .12.

Similiar results were obtained with other cells. One cell no. 6 with platinum electrodes had a resistance at atmospheric pressure

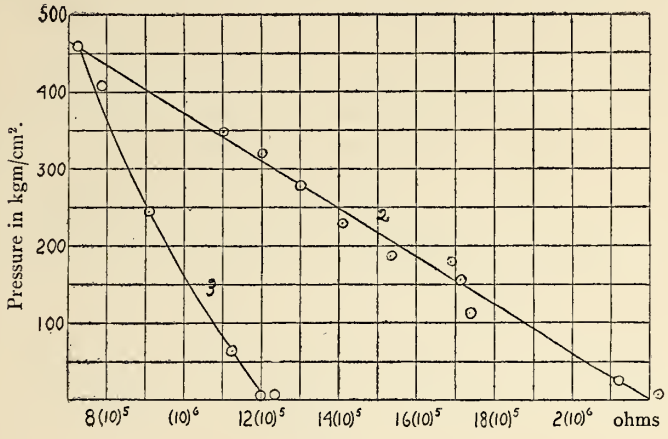

Fig. 2.

of 1,670,000 ohms. Its average decrease per atmosphere was .11 per cent. To compare these three cells, one having round copper electrodes, one with flat copper electrodes and one with platinum

Time.	Pressure, kgm/cm².	Resistance, Ohms.	Change of Resistance per Atmosphere.
2 : 52 P. M.	490	44,600	144
2 : 54	496	44,600	
2 : 57	570		
2 : 59	490	42,400	147
3 : 15	490	48,700	
3 : 20	478	49,700	
3 : 38	453	51,700	139
3 : 45	440	53,100	140
4 : 15	405	56,000	
4 : 25	333	64,300	
4 : 30	250	74,600	156
4 : 35	208	81,900	160
4 : 39	150	90,500	
4 : 44	102	99,900	138
4 : 47	59	106,900	
5 : 18	1	{ 115,000 { 112,000	

electrodes, when 1.4 volts were used in the circuit, the change of resistance was .11 per cent., .12 per cent. and .11 per cent. respectively.

The conductivity of these cells was about doubled when they were exposed to strong light. However they were made at dif-

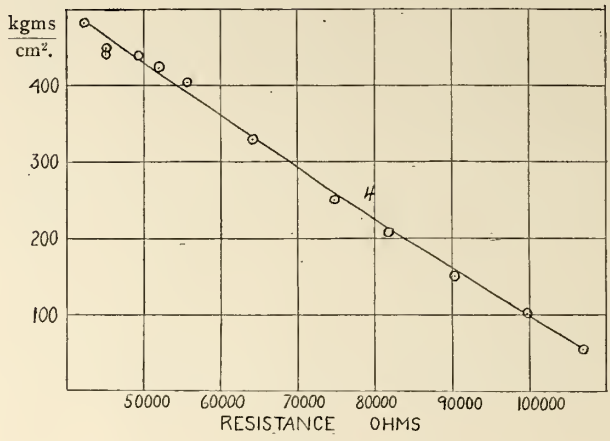

Fig. 3.

ferent times and had electrodes of different shape and material, and the initial resistance is seen to vary more than ten times. It would seem that for selenium cells of a given light sensibility and with con-

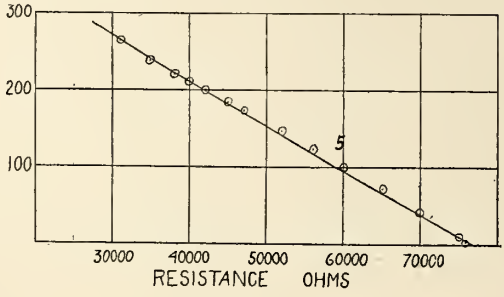

Fig. 4.

stant voltage in the circuit, that the percentage change of resistance per atmosphere is constant.

In Fig. 4 is shown the resistance of Ruhmer selenium cell no. 454 with varying liquid pressures. Three volts were used in the circuit. The sensibility of this cell was about 10 to 1. It is seen that the percentage decrease of resistance for one atmosphere is .23.

In studying air pressures the selenium cells were placed is a piezometer made of car axle steel. The piezometer was connected in series with a steel tank of about 15 cubic feet capacity. The tank was so fitted with valves that the pressure could be let off the piezometer without lowering the pressure in this supply tank. The pressure was furnished by a Norwalk four-stage compressor. About a month before this work was begun with selenium the compressor and tank were used in connection with the liquid-air plant. Lime and potassium hydrate were used as purifiers in the plant. In the first few experiments the air used for pressure was drawn through lime.

Giltay cell no. 92 was the first to be studied in air pressure. On May 20, at atmospheric pressure and about 23° C., the resistance was 1,300,000 ohms in the dark. When 1,400 pounds pressure was applied, the resistance first fell to about 1,200,000, but it kept on decreasing and after about two hours it had reached 520,000 ohms with the pressure on. When the pressure was taken off the resistance recovered immediately to 590,000 ohms.

The condition of the cell afterwards was as follows:

May 22, 1,100,000 to 1,000,000 ohms.
May 23, 14,300 ohms after being under 400 pounds pressure 12 hours.
May 23, 14,400 ohms at atmospheric pressure.
May 24, 7,100 ohms.
May 27, 10,500 ohms.
July 15, 10,300 ohms.

On the last date the selenium was remelted and recrystallized. Its resistance was as follows:

10,300	ohms at	27° C.	
6,000	"	150 "	
1,700	"	204 "	
770	"	209 "	
770	"	213 "	
20,000	"	150 "	
80	"	219 "	
∞	"	218 "	selenium melted.
6,400	"	155 "	
1,900	"	200 "	
4,000	"	183 "	
2,700,000	"	25 "	
50,000	"	25 "	10 cm. from 16 c.p. light.
2,600,000	"	25 "	in dark again.

It is evident from the above table that the resistance of the cell decreased still further as the temperature was raised.

We then tried four cells of our own make under air pressure, and every one behaved just as the Giltay cell did. After being under air pressure from one to twenty hours the resistance reached a final value from which the cells did not recover.

Next the piezometer was filled with kerosene and the pressure was maintained by the air pressure bearing on the surface of the liquid. Several cells were tried and there was no permanent break-

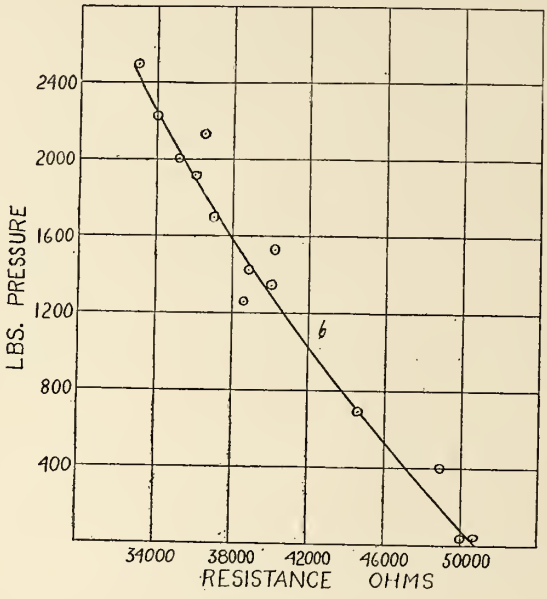

Fig. 5.

ing down of the resistance in any case. When the pressure was raised or lowered the cell changed its resistance almost instantly.

Afterwards these cells which had been tested under liquid pressure were washed in benzene and again placed in air pressure. The resistance then showed no signs of breaking down. In curve 6 (Fig. 5) it is seen how the resistance of the cell varied as the pressure was run up and down again. The pressure was left on more than a day. The sensibility of cell no. 23 was about 8 to 1. The mean

percentage decrease of resistance per atmosphere is seen to be about .22.

We are not prepared to say why the first cells broke down in resistance under air pressure and the last ones did not. There may have been something in the pressure system which was blown out before the last set of observations were taken. The benzene or oil may have prevented the action of the air in the cases in which the resistance did not break down. We do not think the structure of the cells was different in the two cases.

The Light Sensitiveness at Different Pressures.

The selenium cell used in these experiments was the Giltay no. 92 after it had been remelted and reannealed. It was fixed in a hard rubber mounting so that it could be easily and rigidly fastened to electrical connections entering from the side of the piezometer.

The piezometer was made from car axle steel. It was provided with electrical connections similar to some described by Knipp.[1] Opposite one of the electrical connections was an opening to the pressure tank. Opposite the other was a plate-glass window to allow the entrance of light to the cell.

After having considerable difficulty with air pressure around the cell it was decided to use liquid pressure. The piezometer was nearly filled with kerosene, which not only protected the cell from breaking down but also diminished the errors due to temperature. The fact that it absorbed considerable light did not lessen the accuracy of the results.

At first the cell was illuminated by an amyl-acetate standard candle but it was difficult to keep the candle adjusted. The results here published were obtained when an incandescent light giving about 1 c.p. was placed at a distance of 15 cm. from the cell. The time of exposure was 10 seconds. It was regulated by a knife switch placed in the circuit. The light was run by a storage battery giving 6.21 volts during the experiments.

The change of resistance was measured by placing the cell in one arm of a Wheatstone's bridge. A Leeds and Northrup Type H, aperiodic galvanometer was used. The deflection given when the cell was illuminated was taken as indicative of the change of

[1] Phys. Rev., XI., 129.

resistance. This change was found directly by finding what known change of resistance would produce the same deflection. The period of the galvanometer, 3 seconds, and the time of exposure, 10 seconds, were such that no appreciable error entered in the final results. Longer exposures would have been used had it not been that the time for recovery of the light sensitiveness would have increased. Before beginning a series of observations the cell was exposed to the incandescent light for a minute. Then after three-minute intervals the cell was exposed for 10 seconds and the readings were taken. Using constant time intervals insured the same stage of recovery. The same error entered with the pressure on as with the pressure off.

The sensitiveness was compared at pressures varying from 15 pounds to 2,500 pounds. Following is a sample of the series of readings taken. The electromotive force in the Wheatstone's bridge circuit was 11.9 volts.

Time.	Resistance of Selenium Cell.	Readings.		Deflection in mm.	Ohms Change of Resistance.	Percentage Change.	Pressure, Lbs.
3 : 21		− 3.0	27.0	30.0			
3 : 24		15.6	44.6	29.0			
3 : 27		23.4	52.4	29.0			
	2,400,000			29.3	225,000	9.38	15
3 : 30		−19.7	13.5	33.2			
3 : 33		−35.3	− 1.5	33.8			
3 : 36		−39.8	− 6.0	33.8			
	1,860,000			33.6	159,000	8.55	1,970
3 : 39		−20.0	8.7	28.7			
3 : 42		0.8	29.7	28.9			
3 : 45		12.0	40.8	28.8			
	2,520,000			28.8	241,000	9.56	15
3 : 48		−13.5	18.0	31.5			
3 : 51		−36.6	− 4.0	32.6			
3 : 54		−45.6	−13.3	32.3			
	1,970,000			32.1	170,000	8.63	1,890
3 : 58		−33.4	− 4.3	29.1			
4 : 01		−12.4	16.5	28.9			
4 : 04		− 0.3	28.2	28.5			
	2,660,000			28.8	270,000	10.15	15

Summary of Results on Light Sensitiveness at Various Pressures.

Series.		I.	II.	III.	IV.
Mean resistance of selenium cell, ohms.	pressure on	2,607,000	2,270,000	2,133,000	1,915,000
	pressure off	2,850,000	2,878,000	2,435,000	2,530,000
Mean pressure, lbs.		730	2,075	525	1,930
Change of resistance due to light action.	pressure on	185,000	131,000	149,000	164,000
	pressure off	220,000	200,000	178,000	245,000
Percentage change of resistance due to light.	pressure on	7.11	5.77	6.99	8.59
	pressure off	7.70	6.92	7.32	9.70
Change of light effect due to pressure.		0.59	1.15	0.33	1.11
Change of light effect per lb. pressure.		.00083	.00056	.00065	.00058

Area of cell exposed, from .3 to .4 sq. cm.

From the preceding data we get a small but measurable variation in the light sensitiveness at different pressures. For the percentage change of resistance per pound of pressure, the lowest value is .00056 and the highest is .00083. This variation in the different series may have been produced by different temperatures, or by having different areas exposed to the light. However the variation in the candle power of the light may be considered zero. Also the error due to time of exposure was practically zero.

Probably the greatest source of error was due to temperature variation. When the air pressure was turned on from the large supply tank, there was some heating effect in the cell due to the compression of the kerosene. The air in contact with the kerosene probably did not have any immediate effect on the temperature of the cell. In order to approximate the temperature change when the air was turned on, a copper coil was placed in the piezometer. Its resistance was 44.05 ohms at 27.5° C. at atmospheric pressure. One minute after 1,500 lbs. pressure was applied the resistance was 44.20 ohms. After two minutes 44.07 ohms and four minutes 44.06. In five minutes then the temperature had practically returned to its original value.

During the experiments the temperature of the piezometer varied between 24° and 27.5° C., and it was estimated that the cell did not vary more than this. The variation from 6.92 to 9.70 per cent. in the different series may have been partly due to temperature. It was more probably caused by slight differences in the adjustment of the selenium cell and its position with respect to the light.

The Effect of Temperature on the Resistance.

The effect of temperature on the resistance of the selenium cell is shown in curves 7, 8 and 9 (Figs. 6, 7, 8), for the temperatures

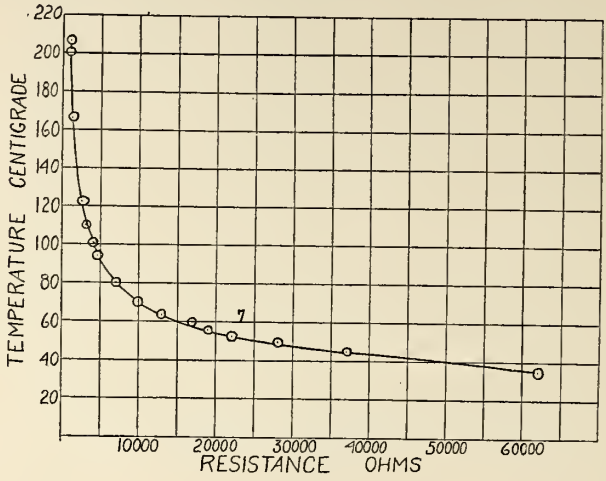

Fig. 6.

indicated. Two points are to be noted, the amount of variation with temperature and the similarity of the variation in the three cells. If the percentage change of resistance were plotted against temper-

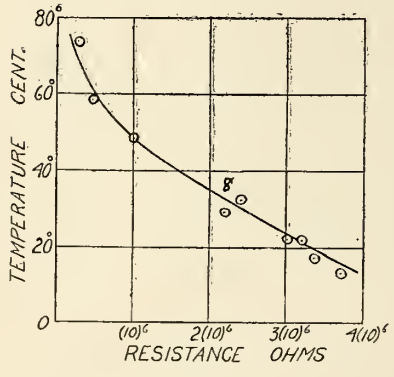

Fig. 7.

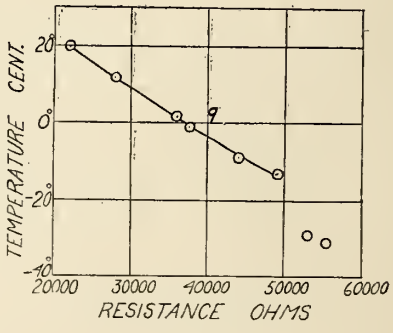

Fig. 8.

ature, the last point would be more readily seen. It was impossible to get the resistance of the cell at liquid-air temperatures because of the cracking of the selenium.

Evidently it would be more satisfactory if we could determine the effects on selenium in terms of specific resistance, but this cannot be done accurately because of the variable amount of selenium in a cell and the structure of the cell.

Light Sensitiveness at Different Temperatures.

To determine the sensitiveness at different temperatures, the Giltay no. 92 was connected in one arm of the Wheatstone's bridge. The cell was placed in a kerosene bath surrounded by a water-bath. About 1 sq. cm. area of the cell was exposed to an incandescent light, of about 1 c.p., and at a distance of 15 cm. About one fifteenth of the total area of the cell was illuminated. The cell was illuminated by light passing above the surface of the water-bath. The thickness of kerosene passed through was not much different from that passed through by the light in the pressure-light experi-

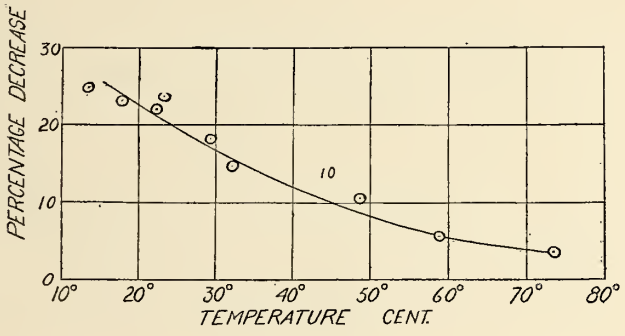

Fig. 9.

ments. The current for the light was obtained from 3 storage batteries giving 6.21 volts. The time of exposure (10 seconds) was regulated by a knife switch. When the cell was exposed there was a deflection of the galvanometer in the manner explained in a previous section and the change of resistance was calculated.

The temperature of the cell was regulated by the surrounding water-bath, which was heated with a bunsen burner or cooled with ice shavings. It will be noticed from the following data that these results are taken as nearly as possible under the conditions prevailing in the study of light sensitiveness at different pressures.

These data are shown graphically in curves 10 and 11 (Figs. 9, 10). In curve 11 we have the sensitiveness expressed for different values of the resistance of the cell, this resistance being a function of the temperature. This resistance is also a function of the state of recovery of the cell and other conditions. But the sensitiveness is probably a function of all these conditions. Consequently

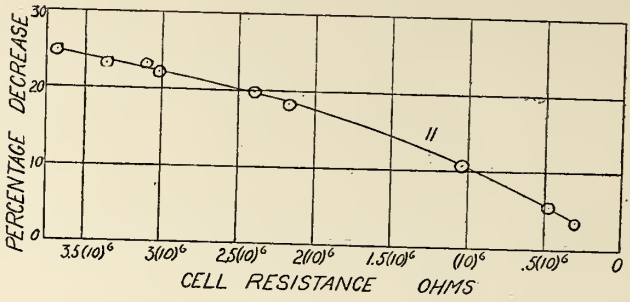

Fig. 10.

we should expect more concordant results in curve 11, since the experiments were made on different days when the state of recovery was different.

The Effect of Hydrogen Peroxide on the Resistance.

We wish to give here some of our own meager observations on the effect of hydrogen peroxide in order to make comparisons with other phenomena.

A cell having a resistance of 80,000 ohms decreased to 50,000 ohms when placed 5 cm. above a surface of hydrogen peroxide. But when the surface of the hydrogen peroxide was enveloped by a sheet of lead, copper, aluminium or even paper there was no appreciable change in the resistance from 80,000 ohms. However, if any of these sheets did not completely cover the surface of the liquid, merely shutting off all the straight line paths from the surface of the hydrogen peroxide to the selenium cell, then the change of resistance was almost as marked as in the first case. When a cell decreased in resistance owing to neighboring hydrogen peroxide, its recovery seemed to be slower than recovery from light,

LIGHT SENSITIVENESS AT DIFFERENT TEMPERATURES.

Time.	Temperature, Centigrade.	Resistance of Cell in Ohms.	Readings.		Deflection, mm.	Change of Resistance.	Percentage Change of Resistance
1 : 54 P. M			— 1.8	62.5	64.3		
1 : 57			— 4.0	60.3	64.3		
1 : 60			— 4.0	59.8	63.8		
2 : 03			— 4.2	59.3	63.5		
	22.3°	3,045,000			64.0	670,000	22.0
2 : 39			8.0	69.2	61.2		
2 : 42			0.4	62.5	62.1		
2 : 45			— 0.2	62.0	62.2		
2 : 48			— 0.2	62.1	62.3		
	17.9	3,370,000			62.0	780,000	23.1
3 : 25			2.0	63.4	61.4		
3 : 28			— 0.8	61.0	61.8		
3 : 31			— 0.8	60.4	61.2		
3 : 34			— 0.8	60.4	61.2		
	13.2	3,725,000			61.4	927,000	24.9
4 : 15			— 5.9	63.5	69.4		
4 : 18			— 10.0	59.9	69.9		
4 : 21			— 13.0	56.6	69.6		
4 : 24			— 15.7	53.0	68.7		
	29.1	2,180,000			69.4	397,000	18.2
5 : 00			— 47.5	28.0	75.5		
5 : 03			— 109.0	33.0	76.0		
5 : 06			— 169.6	92.5	77.1		
5 : 09			— 231.5	154.0	77.5		
	58.6	487,000			76.5	27,400	5.6
9 : 06 A. M.			— 14.2	50.4	64.6		
9 : 09			— 16.3	48.5	64.8		
9 : 12			— 18.4	46.0	64.4		
9 : 15			— 19.2	44.0	63.2		
	23.1	3,212,000			64.2	750,000	23.3
10 : 42			9.0	86.3	77.3		
10 : 45			14.0	85.0	71.0		
10 : 48			— 5.3	74.6	79.9		
10 : 51			— 4.0	72.0	76.0		
	73.4	284,000			76.0	10,400	3.7
12 : 00			— 3.5	69.2	72.7		
12 : 03			— 30.2	43.3	73.6		
12 : 06			— 51.6	21.6	73.2		
12 : 09			— 74.4	— 2.0	72.4		
	48.9	1,070,000			73.0	116,000	10.8

LIGHT SENSITIVENESS AT DIFFERENT TEMPERATURES. — *Continued.*

Time.	Temperature, Centigrade.	Resistance of Cell in Ohms.	Readings.		Deflection, mm.	Change of Resistance.	Percentage Change of Resistance
2 : 19 P. M.			− 7.0	62.7	69.7		
2 : 22			− 11.2	58.7	69.9		
2 : 25			− 14.7	53.6	68.3		
2 : 28			− 18.2	51.3	69.5		
	32.2	2,410,000			69.4	479,000	19.9

pressure or radium effects. It seems that the decrease of resistance was due to something diffusing from the hydrogen peroxide. Certainly there was no radiation of the slightest penetrating power.

In order to study the nature of this change in the selenium cell, we superimposed a light effect upon the hydrogen peroxide effect.

Hydrogen peroxide of strength 30 per cent. was poured on black paper and black cloth within 4 cm. of the Giltay cell no. 92. Some hydrogen peroxide may have got on to the cell itself. The resistance fell from 2,200,000 ohms to 10,000 ohms. Apparently it did not begin to recover until the hydrogen peroxide had evaporated. The time taken was about 20 minutes. When illuminated at this low resistance by a 1 c.p. light, at 30 cm. distance, there was no appreciable change in the resistance. There was no light effect at 18,000 ohms, but when the cell had recovered to 50,000 ohms, a deflection of 5 mm. was produced on the scale, when the cell was illuminated for 10 seconds. The value of the change in resistance was not measured, but it was very small. These results seem to show in a rough way that where there is already a maximum effect due to hydrogen peroxide, there will be produced no additional effect by superimposing a light effect. Also that the light effect will be correspondingly less as the hydrogen peroxide effect increases.

THE EFFECT OF RADIUM.

Under this head is given : (1) The resistance of the selenium cell at different distances from the radium ; (2) the resistance of the cell when different thicknesses of mica are placed between the cell and the radium ; (3) the recovery of the cell after exposure to radium.

The radium used in these experiments was 3 mgm. of 2 to 3,000,000 activity, kindly lent by Professor Rutherford. It was in a rubber case with a mica cover. The mica cover could be removed.

The selenium cell used was made by Ruhmer and numbered by him 454. Its conductivity was increased about 8 times when exposed to light. The circular area exposed to radium was 2.3 cm. diameter.

The resistance was measured by the ordinary Wheatstone's bridge method. The cell was fixed in a hard rubber case. This case was lowered till it touched the top of a brass cylinder 2 inches in diameter. Cylinders of different lengths were used so that the

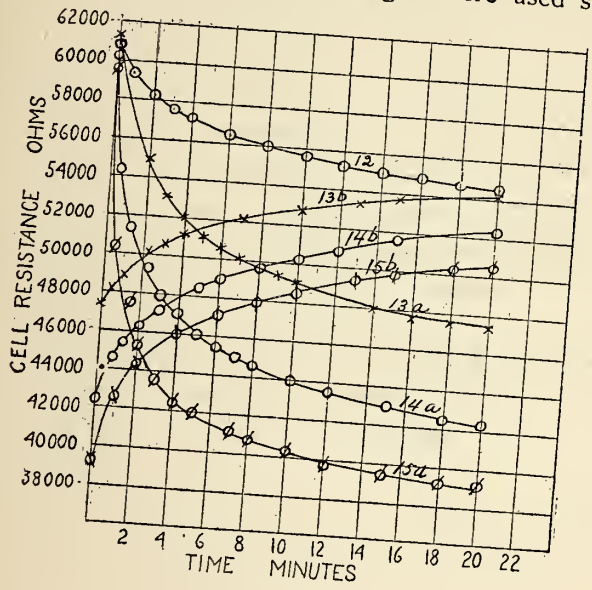

Fig. 11.

effect at different distances could be obtained without disturbing the radium or exposing the cell to light. The results with radium and selenium are shown in the curves of Fig. 11.

Curve 12 shows the decrease of resistance with time when the perpendicular distance from the radium to the cell is 2.6 inches. Curve 13*a* shows the same when the distance is 1.1 inches. Curve 14*a* shows the effect when the distance of the radium is .6 inch, and curve 15*a* is for a perpendicular distance of .1 inch. The

general results of the above-mentioned curves and other similar ones are shown in curve 16 (Fig. 10) in which the exposure is taken for 10 minutes.

The number of particles or rays striking the surface of the sele-

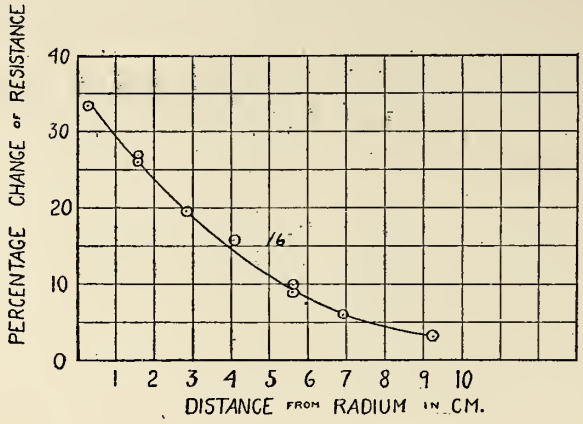

Fig. 12.

nium should vary as the solid angle, if there were no absorption in the intervening space. The following table shows how the change of resistance varies with the solid angle.

Distance of the Radium, mm.	2.6	15.3	27.9	40.6	66	78.7	102.5
Solid angle.	1.5π	0.4π	0.15π	0.078π	0.03π	0.022π	0.012π
Percentage change of resistance.	33.0	26.5	18.5	16.0	9.5	6.2	3.0

From these data it is seen that the change of resistance does not vary as the solid angle. The absorption of the particles by the air does not appear to be capable of explaining the discrepancy. We know that for intense lights the change of resistance is not proportional to the intensity of the light. In the same way we might expect for large values of the solid angle that the change of resistance would not be proportional to the number of particles falling on the selenium surface. Further discussion of the foregoing results will be postponed until the effect of placing thin sheets of mica between the radium and the selenium cell has been considered.

The curves of Fig. 13 show the decrease of resistance of the cell with time when the cell is 1.3 cm. away from the radium. The curves show how the effect varies with time with different thicknesses of mica between the cell and the radium. Of course there was 1.3 cm. of air between the cell and the radium in every case. In obtaining the data for curve 18 the radium was covered with a mica sheet .017 cm. thick. For curve 17 there was an additional mica sheet

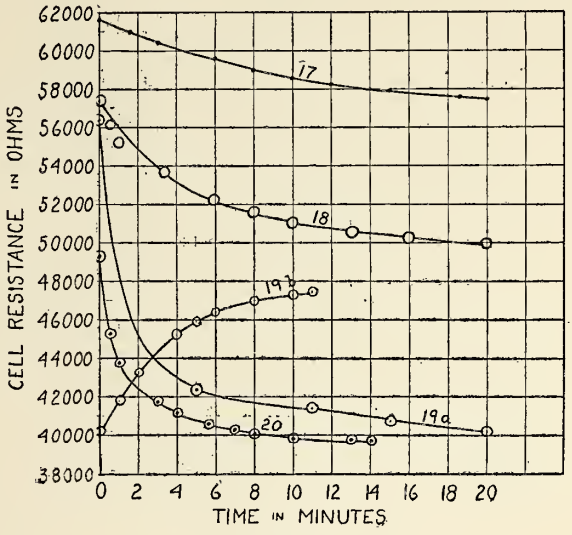

Fig. 13.

.038 cm. thick making a total thickness of .055 cm. But for curves 19*a* and 20 there was no mica over the radium. The difference in these two curves arises from the fact that the state of recovery was not the same in the two cases. Only 14 minutes was allowed for recovery after getting the data for curve 19*a* before taking the observations represented by curve 20.

Fig. 14 shows approximately how the effect varies with different thicknesses of mica interposed. The data for these curves were taken from curves 17, 18 and 19*a*. It could only be approximated however because the state of recovery was different in the several cases. The effect is comparatively very small when .055 cm. of mica is interposed. The absorption of the γ radiation would not warrant such a decrease in the effect. On the other

hand the thinnest piece of mica used would not permit any of the α particles to penetrate it. It therefore follows that some part of the effect is due to the β particles.

The intensity of the β particles after passing through an absorbing medium is expressed by the equation,

$$i = i_0 e^{-\lambda d},$$

where i_0 is the value of the intensity for no absorbtion, d is the thickness of the absorbing material, and λ is the coefficient of absorption.

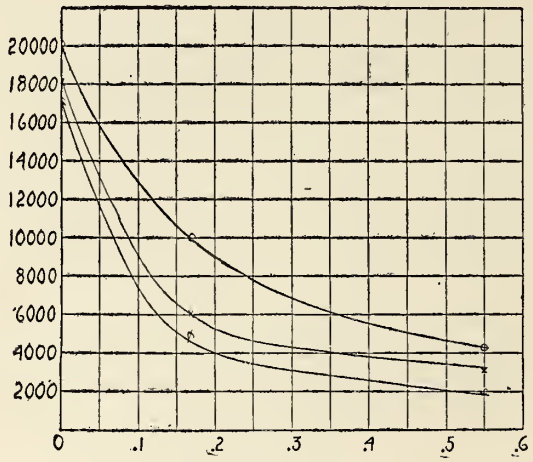

Fig. 14.

To find the coefficient of absorption from our data we may take from curve 23 the intensity of the radiation after passing through .02 and .05 cm. of mica. For either of these thicknesses the intensity of the radiation is about proportional to the change of resistance, and also there can be no α particles in either case. From the previous equation we get for different thicknesses of mica,

$$\lambda = \frac{\log_e \frac{i_1}{i_2}}{-d_1 d_2}.$$

Putting in the values for a 5 minute exposure we get

$$\lambda = 23.0.$$

For a 10-minute exposure as taken from curve 22, the value of the coefficient is

$$\lambda = 14.2.$$

Strutt gives 10.8 for the value of λ, the coefficient of absorption, for the β rays from radium. Our values are of the same order of magnitude as that given by Strutt.

In order to see if the α particles play any part in the change of resistance, we may refer again to curve 23. If we assume the density law for the absorption of the α particles, they would be almost completely absorbed by .015 cm. of mica. Assume then that all the change of resistance, 5,200 ohms, when .015 cm. of mica is interposed is due to the β rays. By use of the equation $\log i/i_0 = e^{-\lambda d}$ it is found that if 5,200 represents the intensity of the β rays after passing through a thickness of mica of .015 cm., then the intensity for no absorption should be represented by 7,400. For these intensities the change of resistance should vary less rapidly than the change of intensity, so that for zero thickness of mica, we should expect a change in resistance of less than 7,400 ohms. But the curve 23 shows that the change of resistance for no mica interposed is 17,000 ohms. Since this value represents a larger value of the intensity, we are led to believe that where there is no absorption the α particles have a greater effect than do the β particles. However we do not know whether any of this effect which we have attributed to the α particles may be due to the emanation.

Again referring to the variation of resistance with distance from the radium it is seen that beyond 5 cm. the change of resistance is almost proportional to the solid angle subtended. The slight discrepancy here can be accounted for by the absorption of the β particles in air. The γ particles would suffer no appreciable absorption under such circumstances. For distances less than 5 cm. the change of resistance decreases less rapidly than does the solid angle. But no conclusions can be drawn from this since the change of resistance is not proportional to the intensity.

The effect of radium on the selenium cell has been investigated by Himstedt and Bloch. Himstedt[1] found a one per cent. decrease of resistance in the selenium cell. The radium rays had to pass

[1] Ann. der Physik, 1901, 4, p. 535.

through an opaque paper and one centimeter of air. Bloch[1] found a cell to decrease from 30,100 to 29,000 ohms and this through a sheet of paper. In another case a cell decreased from 654,000 to 640,000 ohms in 10 minutes time. The radium used was of activity about 1,000. Himstedt does not state the activity of his radium, but judging from the percentage decrease it was probably not much different from that used by Bloch. In either of these cases the effect was so slight and the data so limited that we could not expect to arrive at any conclusion as to how the radium affected the selenium.

The recovery of the selenium cell after exposure to radium is shown in curves 13*b*, 14*b*, 15*b*, 19*b* and 26. It is apparent that the recovery is not as rapid as the recovery from the same decrease of resistance due to light. However it does return eventually to approximately the initial value. In curve 26 (Fig. 15) is shown the recovery when there was about a 35 per cent. decrease of resistance due to radium. Curve 25 shows the recovery when the same Ruhmer cell had its resistance decreased 87 per cent. by light. Unfortunately the recovery for a 35 per cent. decrease was not studied, but the recovery would evidently be much faster. In curve 25 is shown the recovery of cell 4 when there was a 10 per cent. decrease of resistance by light. The conclusion is that for the same decrease of resistance the recovery from the effect of radium is much slower than the recovery from the effect of light.

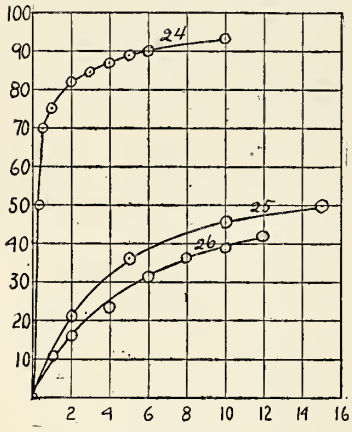

Fig. 15.

Discussion of Results.

The purpose of this paper is to examine the effects of the various agencies that change the resistance of the selenium cell and to cor-

[1] Compt. Rendus, CXXXII., p. 914.

relate them in so far as possible. The selenium cell varies in resistance when exposed to temperature change, to pressure change, to light, to radium rays, to hydrogen peroxide and to other conditions not mentioned in this paper. The question arises as to whether these resistance changes are ultimately due to the same cause. We may state at the outset that we cannot completely correlate our results but we hope that in the near future an hypothesis may be set up which will satisfactorily and completely explain all the various selenium phenomena.

First as regards pressure. The pressure effect must be a genuine effect in the selenium. The change in resistance due to pressure cannot be due to change in contact resistance between the selenium and the electrodes. For suppose,

R is the contact resistance.

r is the variable resistance in the selenium itself.

ΔR is the change of contact resistance due to pressure.

Δr is the change of resistance due to light.

Then when the pressure is off, the percentage change of resistance in the whole cell would be

$$\frac{\Delta r}{R + r} \times 100.$$

When the pressure is on the cell, the light effect being the same, the percentage change of resistance would be

$$\frac{\Delta r}{R + \Delta R + r} \times 100.$$

The ratio of the percentages of change would be,

$$\frac{\text{pressure on}}{\text{pressure off}} = \frac{R + r}{R + \Delta R + r}.$$

If the pressure decreased the contact resistance, ΔR would be negative, and the ratio necessarily greater than one. On examining our data it is seen that the value of this ratio is slightly less than unity in every case, and it is clear then that the change of resistance due to pressure cannot be due to change of contact resistance. We may also arrive at the same result by other reasoning. $\Delta R/R$ is

considerable, sometimes approaching values as large as .5. If the change due to pressure were in the contact between the selenium and the electrodes, we should expect a variation in the light sensitiveness approaching values as large as 50 per cent. But in comparison with values as large as 50 per cent. the variation may be considered zero.

Next consider the similarity of the nature of the decrease of resistance due to temperature and that due to pressure. It is to be noted that in pressure effects as well as in temperature effects the sensitiveness of the cell to light seems to be a function of the resistance of the given cell. This can best be understood by looking at the curves of Fig. 16. In I., II., III. and IV. is shown how the sensitiveness varies with the resistance, when the change of

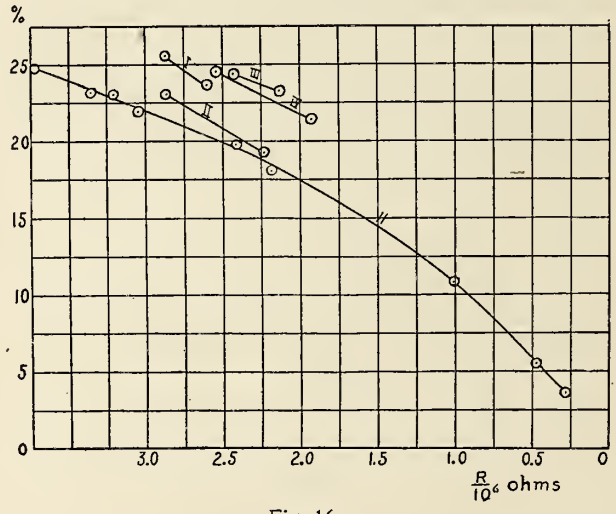

Fig. 16.

resistance is produced by a variation of the pressure. In series IV. of the observations on the sensitiveness at different pressures it was estimated that .4 sq. cm. area of the cell was exposed to light. Consequently to find the sensitiveness for the exposure of one square centimeter area the value found previously was divided by .4. For the same reason the other three series were divided by .3. In curve II is shown how the sensitiveness varies with the resistance, when the change of resistance is produced by temperature variation.

Within the limits of error of the experiments it is seen that the rate of change of sensitiveness is the same for all the curves, and we may conclude that the sensitiveness to light is probably dependent upon the resistance, whether that be conditioned by temperature or pressure.

It is seen from the previous data that the pressure effects take place almost instantly upon the application of the pressure. With the exception of a small lag the selenium cell, when exposed to temperature changes in a liquid bath, rises to a position of electrical equilibrium even quicker than does an ordinary thermometer. This correlation is what we should expect. However if the quantity of selenium in the cell is great and the cell is surrounded by an air bath, the cell may be quite sluggish in changing its resistance with the temperature of the bath.

The rough work done with hydrogen peroxide will not of itself permit of any definite conclusions, but the following seems to be true. The change of resistance in the dark is of such a nature that if light is allowed to fall on the cell there is no additional change in the resistance, providing only that the change produced by the hydrogen peroxide is sufficiently great. The rate of recovery from exposure to hydrogen peroxide is very slow, resembling the recovery from the effects of radium.

With increased temperature or increased pressure, or hydrogen peroxide exposure the change of resistance due to light is correspondingly less. So far as electrical conductivity is concerned, all these conditions seem to take the selenium toward a certain equilibrium state.

Summary.

1. The selenium cell changes its resistance with a change in the mechanical pressure on its surface. The pressure produces a real change in the resistance of the selenium itself. For the cases noted the percentage change of resistance for one atmosphere lies between .05 and .30. This value is also a function of the temperature and the electromotive force applied in measuring the resistance.

2. An increase of pressure or a rise of temperature lowers the light sensitiveness of the selenium cell.

3. The light sensitiveness is a function of the resistance of the given cell, whether this resistance be conditioned mainly by temperature, light, radium or hydrogen peroxide.

4. The effect of radium and of hydrogen peroxide is to decrease the resistance very markedly, as much as 35 and 99 per cent. respectively.

This work was carried on in the Physics laboratory of the University of Illinois and the writers wish to acknowledge their indebtedness, to Professor A. P. Carman for apparatus placed at their disposal and for his help in the early part of the work; also to Professor E. Rutherford for kindly lending the radium used, and to Professor O. W. Richardson for several valuable suggestions.

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